Is the wind stress forcing essential for the meridional overturning circulation?

A. Timmermann
Leibniz-Institut für Meereswissenschaften IFM - GEOMAR Duesternbrooker, Kiel, Germany

H. Goosse
Institut d'Astronomie et de Géophysique G., Lemaitre, Université Catholique de Louvain, Louvain-la-Neuve, Belgium

Received 6 October 2003; accepted 19 January 2004; published 21 February 2004.

[1] We use a global coupled atmosphere-ocean sea-ice model of intermediate complexity to demonstrate that wind-forcing is a crucial element to sustain meridional overturning flow in the Atlantic. Neglecting wind-stress in our multi-century-long simulations leads to a complete shutdown of the conveyor belt circulation. This result may have tremendous impacts for an assessment of the sensitivity of 2-d climate models which typically do not capture wind-driven gyres. It is argued that wind effects may be a key element in determining the fate and length of a collapsed THC state. Possible paleo implications will be discussed. *INDEX TERMS:* 4532 Oceanography: Physical: General circulation; 4255 Oceanography: General: Numerical modeling; 4512 Oceanography: Physical: Currents; 4504 Oceanography: Physical: Air/sea interactions (0312); 4267 Oceanography: General: Paleoceanography. **Citation:** Timmermann, A., and H. Goosse (2004), Is the wind stress forcing essential for the meridional overturning circulation?, *Geophys. Res. Lett.*, *31*, L04303, doi:10.1029/2003GL018777.

1. Introduction

[2] The thermohaline circulation (THC) is a key element of the Northern Hemispheric climate system. It carries a substantial amount of heat and saline waters poleward, thereby altering the atmospheric circulation and sea ice. Despite of the importance of this circulation many fundamental questions have not been answered satisfactorily: What drives the THC? What are the roles of convection, turbulent mixing and diffusion? What is the role of the wind-driven circulation? While the second question has been studied extensively [e.g., *Welander*, 1986; *Nilsson et al.*, 2003; *Marotzke*, 1997, and many others] the latter has received only very little scientific attention [e.g., *Weaver et al.*, 1993; *Toggweiler and Samuels*, 1995; *Schiller et al.*, 1997; *Oka et al.*, 2001]. Recent attempts [*Oka et al.*, 2001] to quantify the role of wind forcing for thermohaline flow have revealed that horizontal Ekman flow in the subpolar gyre as well as Ekman pumping [*Schiller et al.*, 1997] provide surface salinity sources which prevent the formation of polar/subpolar haloclines, thereby stabilizing the THC. Furthermore, Ekman pumping can be a very important factor in preconditioning oceanic convection which eventually may influence thermohaline flow, as pointed out by *Killworth* [1983] and *Schiller et al.* [1997]. Previous studies [*Oka et al.*, 2001] address this issue systematically. *Oka et al.* [2001] find that both horizontal and vertical salinity transports in the northern North Atlantic are crucial elements for the meridional overturning circulation. Neglecting either of them leads to a shutdown of the meridional overturning. However, this study suffers from several model shortcomings such as a parameterized atmosphere, a lack of sea-ice dynamics and of an arctic ocean. Hence, it is timely to check the general conclusions once more in a physically more complete setup using a 3-d global atmosphere-ocean model. Our general conclusion is consistent with the findings of *Oka et al.* [2001]. Wind forcing is needed to maintain meridional overturning flow. The fundamental question to be addressed here is what happens to the meridional overturning circulation in the North Atlantic when wind-forcing is neglected. We use the global coupled atmosphere-ocean-sea ice model ECBilt-Clio which has been described extensively in the literature [*Opsteegh et al.*, 1998; *Goosse and Fichefet*, 1999; *Goosse et al.*, 2002]. Here we analyse three simulations performed with this coupled model: The first experiment (EXP1) is a 700-year long control simulation forced by pre-industrial CO_2 concentrations. In EXP2 a persistent freshwater anomaly of 0.4 Sv is injected into the North Atlantic between 50–70°N leading to a shut-down of the THC. The length of this simulation is 280 years. Another coupled simulation is performed (EXP3) for 16300 years in which no wind-stress forcing is applied to the ocean.

2. Main Results

[3] Figures 1 and 2 show that in both experiments EXP2 and EXP3 the meridional circulation collapses quickly within the first few hundred years, whereas it remains stationary in the control simulation (EXP1).

[4] EXP3 has been continued for 16300 years and shows some ultra-low-frequency oscillations like those discussed by *Oka et al.* [2001] and *Winton* [1993]. The prolonged off-state of the THC is accompanied by an overall diffusive warming of the deep ocean until a threshold temperature is reached. Eventually, the stratification in the ocean becomes unstable and a rapid flush of the THC is induced, which vents the stored heat of the deep ocean to the surface. Subsequently the flush stops after a few hundred years and the deep-decoupling phase starts once more. Our modeling results show that the off-state of the THC is oscillatory unstable. During the off state the polar regions of both

0094-8276/04/2003GL018777

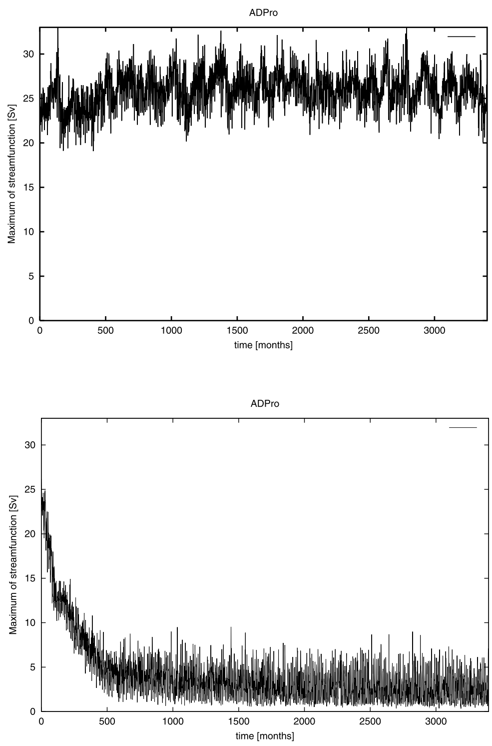

Figure 1. Maximum of the meridional streamfunction in the North Atlantic [Sv] EXP1 (upper panel), EXP2 (lower panel). Time axis is in units of months.

hemispheres are not able to form a significant amount of deep water any longer.

[5] Thus, wind forcing is a crucial element to sustain the meridional overturning circulation in the North Atlantic, in accordance with *Oka et al.* [2001]. The thermohaline component of the overturning circulation operates on a mean zonal and meridional density gradient, which is partly maintained by the wind-driven salinity and heat transports. This illustrates also the difficulty of separating wind-driven and thermohaline flow, since the wind-driven flow contributes to thermohaline forcing. Nevertheless an attempt will be made here using EXP1-3. The final stages of EXP2 and EXP3 are both characterized by a lack of North Atlantic Deep Water formation. Hence their density driven surface flow in the North Atlantic is quite similar. The main difference is that EXP2 still maintains the wind-driven circulation, although the wind-pattern may have changed a little between the two simulations. In comparison to EXP3, EXP2 is characterized by a much stronger Goldsbrough circulation [*Goldsbrough*, 1933] due to the imposed freshwater forcing. Neglecting these second order effects the difference of the surface flow patterns of EXP2 and EXP3 (Figure 3) represents the wind-driven circulation.

[6] Not surprisingly, the major wind-driven features are the subtropical and subpolar gyres as well as the Antarctic Circumpolar Current. Assuming the wind-driven circulation in EXP1 and EXP2 to be similar the major difference between EXP1 and EXP2 is the direct density-driven meridional overturning circulation in the Atlantic due to freshwater and heat fluxes. In fact the atmospheric circulation responds to a collapse of the thermohaline circulation by an increased surface wind stress. However, these wind-stress changes are small as compared to the total magnitude of the surface winds, which are neglected in EXP 3. The associated surface flow pattern (Figure 3, right panel) is quite instructive: One observes the main features of the surface conveyor belt flow. A southern Atlantic warm water branch flowing from the southern Indian ocean to the South Atlantic around the southern tip of Africa. This flow is also visible in the undifferenced current data of EXP1. Furthermore, we see a strong Brazil current which splits at 25°N into two major branches−one flowing northward parallel to the western boundary current, the other one opposing the wind-driven subtropical gyre circulation and flowing northward on the eastern boundary. Both current branches merge again in the Greenland-Iceland-Norwegian (GIN) Seas. The diagnosed thermohaline flow tends to reinforce the Gulf Stream transport whereas it slows down the subpolar gyre. The model-based decomposition into wind-driven (EXP2-EXP3) and freshwater and heat flux-driven thermohaline (EXP1-EXP2) flow (similar to *Manabe and Stouffer* [1988]) is reasonable as can be deduced (not shown) from

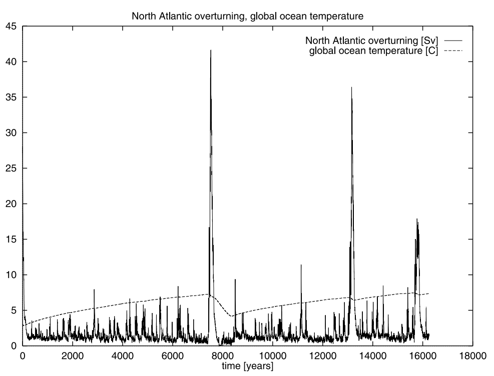

Figure 2. Maximum of the meridional streamfunction in the North Atlantic [Sv] (solid) and global ocean mean temperature [C] (dashed) for EXP3. Time axis is in units of years.

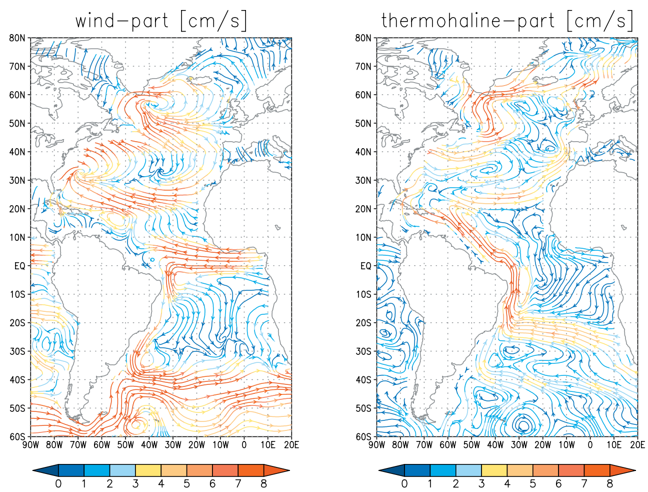

Figure 3. Circulation splitted into a "wind-driven" and a "thermohaline" part.

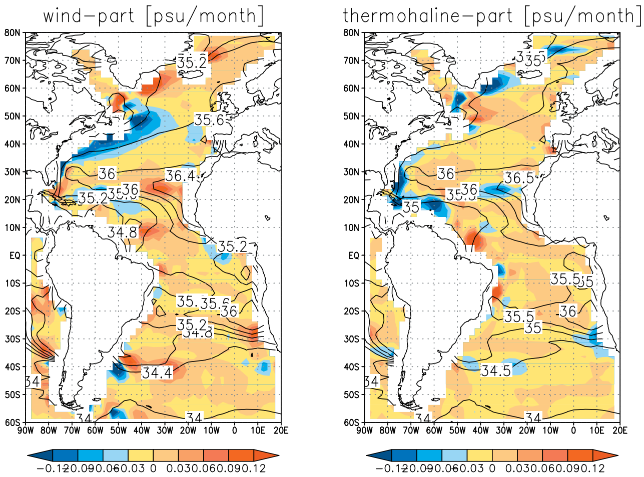

Figure 4. Left: Time averaged surface salinity field of EXP1 and surface salinity transport (shading) due to the wind driven circulation ($[\vec{U}_{\rm wind}]$ $[\nabla S_{\rm EXP1}]$). Right: As left but for the "thermohaline" circulation.

a comparison between the sum of these parts with the total circulation from EXP1. The role of the wind-driven circulation in maintaining meridional overturning flow in the North Atlantic is complex. One important part is horizontal surface layer salinity advection which prevents the formation of a polar, subpolar halocline, thereby stabilizing thermohaline flow. Figure 4 displays the wind-driven and thermohaline contributions to the mean surface salinity advection in the North Atlantic. The wind-driven circulation contributes up to 0.15 psu/month to the salinity tendency in the GIN seas and the area of the east Greenland current, whereas the residual thermohaline flow generates a buoyance forcing of similar magnitude but reverse sign. Hence, wind-driven flow prevents the formation of haloclines in the GIN sea. If, however, the meridional overturning circulation is active the meridional overturning flow transports a huge amount of salinity northward, as can be seen from the large salinity differences in high latitudes between EXP1 and EXP2 (not shown). Similar results were discussed by *Manabe and Stouffer* [1988].

[7] A background salinity field is generated by the local freshwater forcing. The wind-driven and the thermohaline circulation serve together as coupled horizontal (and vertical) advective re-distributors of this inital large-scale surface salinity field. If the wind-driven part is neglected, a salt deficit occurs in high latitudes. Apart from this large-scale effect on thermohaline there may be local effects which help to weaken the meridional overturning flow further. In EXP2 and EXP3 a salt deficit in high latitudes leads also to an increase of the sea ice extent of more than 8×10^6 km^2 in annual mean, i.e. nearly a doubling. This induces an isolating effect on the ocean that prevents further heat release from the ocean to the atmosphere, thereby stabilising the water column. Furthermore, the presence of sea ice modifies the surface momentum budget. When sea-ice is thin, the wind stress is transmitted to the ocean surface with only a weak influence of the ice. For a compact and thick ice cover on the other hand, the presence of ice can induce a reduction of the ocean surface stress by more than 80% compared to the total wind stress [e.g., *Goosse and Fichefet*, 1999]. This reduction of the wind stress influences the surface currents and thus the oceanic salinity transport. Hence an initial weakening of the winds of sufficient amplitude can trigger a chain reaction of large-scale and local processes which involve reduced salinity transport, increased formation of sea-ice and stabilization of the state without oceanic convection. Eventually this will affect the large-scale meridional overturning circulation.

3. Summary and Conclusion

[8] Using a fully coupled global atmosphere-ocean sea-ice model we have shown for the first time that wind-forcing plays a substantial role in maintaining large-scale thermohaline flow in the North Atlantic. A model experiment without wind-forcing (EXP3) leads to a collapse of the meridional overturning circulation. Density gradients needed to drive thermohaline flow can not be maintained without wind-forcing. Wind-forcing of the THC has three important contributions: horizontal Ekman-driven salinity transport due to the wind-driven circulation [*Weaver et al.*, 1993], vertical salinity transport [*Oka et al.*, 2001] and the preconditioning of oceanic convection [*Killworth*, 1983] due to Ekman pumping. Furthermore, we have shown for the first time that deep-decoupling oscillations as described by *Winton* [1993] can be simulated using a global 3-d coupled atmosphere-ocean-sea ice model using full topography. Our results suggest that the THC off-state is oscillatory unstable. Our modeling results have important implications for the interpretation of paleo records of the last glacial period. Heinrich events [*Heinrich*, 1988] have influenced the THC substantially. They were also accompanied by an equatorward shift of the sea-ice margin in the Northern Hemisphere. Sea-ice is not only an insulating factor for oceanic freshwater and heat forcing, but also an insulator for the atmosphere-ocean momentum exchange. In particular in the Northern Hemisphere, a larger sea-ice area will be associated with a strong modification of wind-driven salinity transports with the potential to weaken the THC and to increase the sea-ice cover further. Some of the present climate models of intermediate complexity [e.g., *Crucifix et al.*, 2002] employ a 2-D ocean model that captures the wind-driven ocean circulation in a parameterized manner. In contrast to our 3-d simulations and those of *Oka et al.* [2001] the 2-d model of *Crucifix et al.* [2002] does not simulate a collapse of the overturning circulation (Michel Crucifix, personal communication), in response to weakened winds. This indicates that 2-d models of the THC miss an important feedback. Overall, our study suggests that the wind-driven circulation is a pre-requisite for the set-up of meridional overturning flow in the North Atlantic. Further studies using coupled general circulation models are needed to confirm this far-reaching conclusion. State-of-the art models do not agree on the prediction of the future evolution of the intensity of the thermohaline circulation. Several mechanisms have been suggested to explain the disagreement: such as a different response of the meridional freshwater transport in the various models and an influence of tropical dynamics. Our experiments suggest that the influence of the wind stress must be taken into account in an assessment of the different behaviour of the models.

[9] **Acknowledgments.** A. Timmermann is supported by the Deutsche Forschungs Gemeinschaft. H. Goosse is Research associate with the Belgian National Fund for Scientific Research.

References

Crucifix, M., M. F. Loutre, and P. Tulkens (2002), Climate evolution during the Holocene: A study with an Earth system model of intermediate complexity, *Clim. Dyn.*, *19*, 43–60.

Goldsbrough, G. R. (1933), Ocean currents produced by evaporation and precipitation, *Proc. R. Soc. London Ser. A*, *141*, 241–248.

Goosse, H., and T. Fichefet (1999), Importance of ice-ocean interactions for the global ocean circulation: A model study, *J. Geophys. Res.*, *104*(C10), 23,337–23,356.

Goosse, H., F. M. Selten, R. J. Haarsma, and J. D. Opsteegh (2002), Large sea-ice volume anomalies simulated in a coupled climate model, *Clim. Dyn.*, *10*, doi:10.1007/s0382-002-0290-4.

Heinrich, H. (1988), Origin and consequences of cyclic ice rafting in the North Wast Atlantic Ocean during the past 130,000 years, *Quat. Res.*, *29*, 143–152.

Killworth, P. D. (1983), Deep convection in the world ocean, *Rev. Geophys. Space Phys.*, *21*, 1–26.

Manabe, S., and R. J. Stouffer (1988), Two Stable Equilibria of a Coupled Ocean-Atmosphere Model, *J. Clim.*, *1*, 841–866.

Marotzke, J. (1997), Boundary mixing and the dynamics of the three-dimensional thermohaline circulations, *J. Phys. Oceanogr.*, *27*, 1713–1728.

Nilsson, J., G. Broström, and Gösta Walin (2003), The thermohaline circulation and vertical mixing: Does weaker density stratification give stronger overturning, *J. Phys. Oceanogr.*, *33*, 2781–2795.

Oka, A., H. Hasumi, and N. Suginohara (2001), Stabilization of thermohaline circulation by wind-driven and vertical diffusive salt transport, *Clim. Dyn.*, *18*, 71–83.

Opsteegh, J. D., R. J. Haarsma, F. M. Selten, and A. Kattenberg (1998), ECBILT: A dynamic alternative to mixed boundary conditions in ocean models, *Tellus*, *50A*, 348–367.

Schiller, A., U. Mikolajewicz, and R. Voss (1997), The stability of the North Atlantic thermohaline circulation in a coupled ocea-atmosphere general circulation model, *Clim. Dyn.*, *13*, 325–347.

Toggweiler, T. R., and B. Samuels (1995), Effect of Drake Passage on the global thermohaline circulation, *Deep Sea Res.*, *42*, 477–500.

Weaver, A. J., J. Marotzke, P. F. Cummins, and E. S. Sarachik (1993), Stability and variability of the thermohaline circulation, *J. Phys. Oceanogr.*, *23*, 39–60.

Welander, P. (1986), Thermohaline effects in the ocean circulation and related simple models, in *Large-scale transport processes in the oceans and atmosphere*, edited by J. Willebrand and D. L. T. Anderson, D. Reidel, Norwell, Mass. (imprint of Kluwer Acad.).

Winton, M. (1993), Deep decoupling oscillations of the oceanic thermohaline circulation, in *Ice in the climate system*, edited by W. R. Peltier, pp. 417–432, Springer Verlag, Berlin.

H. Goosse, Institut d'Astronomie et de Géophysique G., Lemaitre, Université Catholique de Louvain, Louvain-la-Neuve, Belgium.

A. Timmermann, Leibniz Institut für Meereswissenschaften, Kiel, Germany. (atimmermann@ifm.uni-kiel.de)